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Leptogenesis with Minimal Flavor Violation

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Outline

- Introduction: neutrinos, LFV & Leptogenesis

- LFV & Leptogenesis within models satisfying the “Minimal Flavor Violation” hypothesis

  VC, B. Grinstein, G. Isidori, M. Wise, Nucl.Phys. B 728 (2005) 121 (hep-ph/0507001)

  VC, G. Isidori and V. Porretti, Nucl.Phys. B 763 (2007) 228 (hep-ph/0607068)

- “Hot” recent developments (“flavor” and “memory”) and their impact on MFV-leptogenesis

Introduction: neutrinos, LFV & Leptogenesis

Connecting LFV, CPV and BAU

Type I $\longleftrightarrow$ See-saw mechanism for m_ν

$$\mathcal{L} \supset \frac{1}{2}(M_R)_{ij}\, \nu_R^{Ti}\, C\, \nu_R^j \;-\; \lambda_\nu^{ij}\, \bar{\nu}_R^i\, (H_c^\dagger\, L_L^j) + \mathrm{h.c.}$$

Super-heavy ν_R

M_R : L violation
λ_ν : CP and L_i violation

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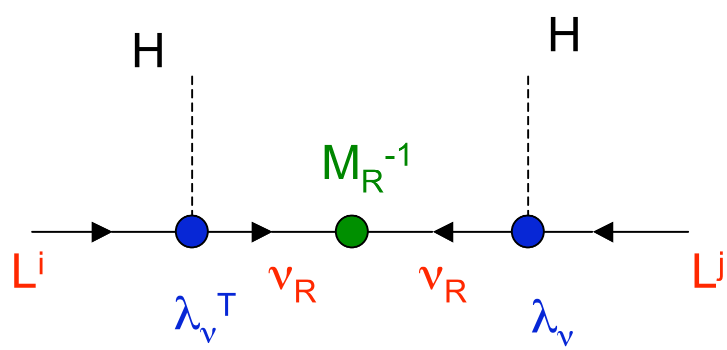

$m_\nu \sim v_{ew}^2\ \lambda_\nu^T M_R^{-1} \lambda_\nu$

Connecting LFV, CPV and BAU

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1) $\cancel{C}$P and $\cancel{L}$ out-of-equilibrium decays of N_i ($T \sim M_R$) $\Rightarrow n_L$

$$\boxed{\Gamma(N_i \to l_k\, H^*) \neq \Gamma(N_i \to \bar{l}_k\, H)}$$

2) B+L violation (sphalerons) $\Rightarrow$

$$\boxed{\eta_B \equiv \frac{n_B}{n_\gamma} \neq 0}$$

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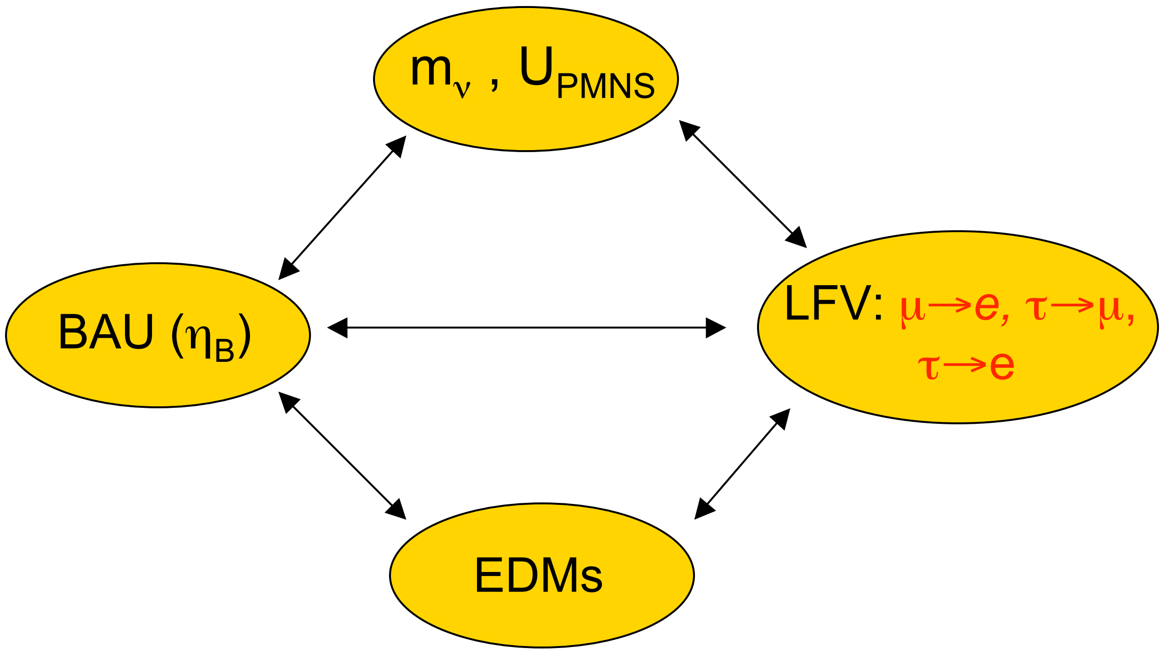
If CP & L_i violation is communicated to particles with mass Λ~TeV

Observable LFV

Observable lepton EDMs

Key questions

- Can we identify signatures for the see-saw scenario?



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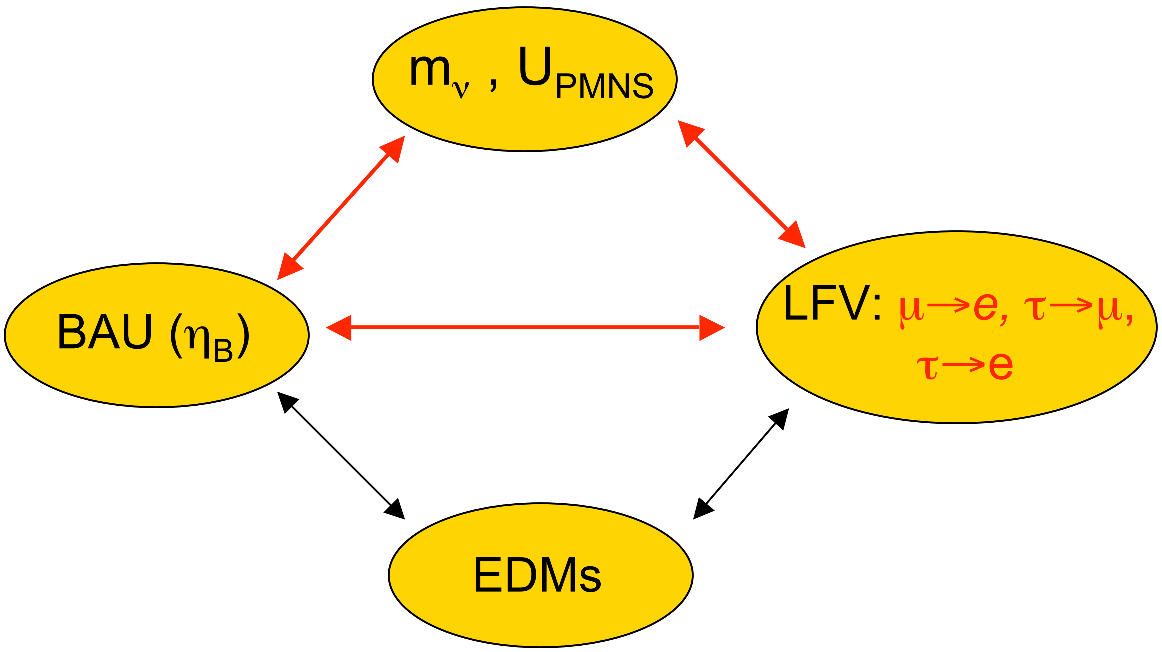

- In this talk, I discuss (some of) these correlation in the context of MFV

Minimal Flavor Violation

The "Flavor Problem":

- Clash between *theoretical expectation* of "new physics" at the ~TeV scale and *experimental observations in rare FCNC processes (K, B, μ, τ)*

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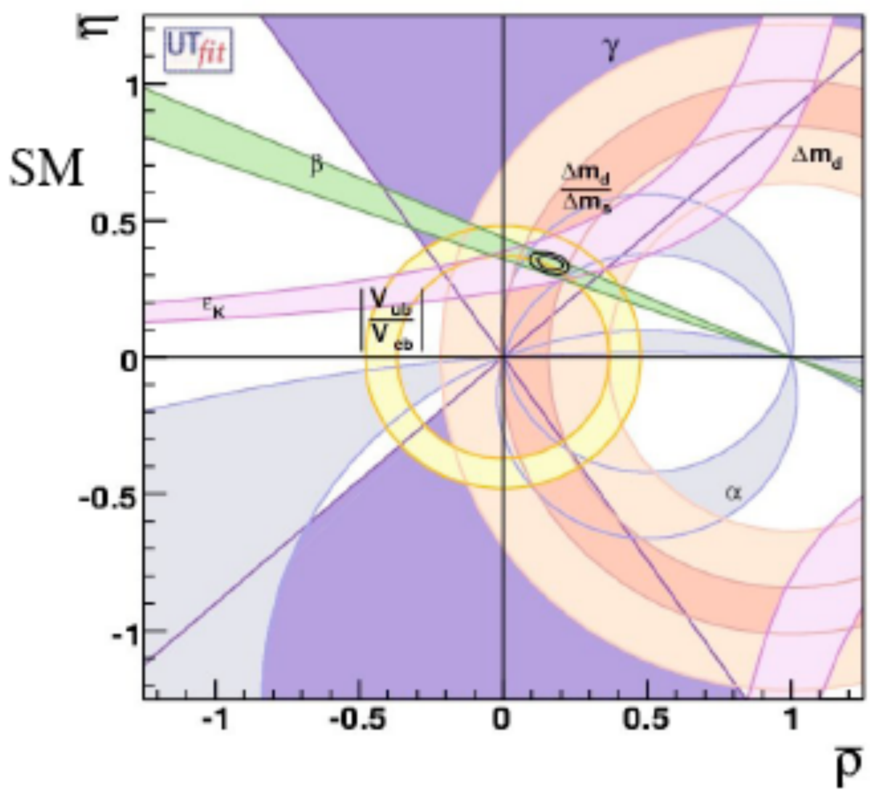
- Quark Sector: the unreasonable success of the CKM paradigm!



$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\longrightarrow$ $\boxed{\Lambda_{NP} > 10^{3\text{-}4}\ \text{TeV}}$

- Lepton sector: severe constraints from FCNC of charged leptons

$$\longleftrightarrow \qquad C_{\mu e} \frac{v_{\rm ew}}{\Lambda^2} \bar{\mu}_R \, \sigma^{\mu\nu} e_L \, F_{\mu\nu}$$

[$\mu \to e\, \gamma$ in SUSY]

$$\boxed{BR(\mu \to e\gamma) < 1.2 \times 10^{-11} \quad \longrightarrow \quad \Lambda/\sqrt{C_{\mu e}} \; > \; 2 \times 10^4 \,\mathrm{TeV}}$$

(95% C.L.)

Λ >> TeV [at least for "flavored" d.o.f., Λ_{FV} ~ $10^{3\text{-}4}$ TeV]

Λ ~ TeV

Effective operators reflect underlying symmetry

What type of symmetry ?

$$\mathcal{L}_{\text{eff}} = \underbrace{\mathcal{L}_{\text{Gauge}}[\psi_i, A_k] \; + \; \mathcal{L}_{\text{Higgs}}[H, A_k, \psi_i}_{\mathcal{L}_{SM}}; v, \lambda] \; + \; \sum_{d \geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} O_n^{(d)}[\psi_i, A_k, H]$$

Georgi-Chivukula 1987
Hall-Randall 1990
Buras et al 2001
D'Ambrosio et al 2002

- $\mathcal{L}_{SM}$: *no exact flavor symmetry!*
- $G_F = U(3)^5$ (invariance of $\mathcal{L}_{\text{Gauge}}$) is broken by Yukawa couplings **

$$\boxed{\bar{Q}_L^i \, \lambda_D^{ij} \, d_R^j \, H \qquad \bar{Q}_L^i \, \lambda_U^{ij} \, u_R^j \, H_c \qquad \bar{L}_L^i \, \lambda_e^{ij} \, e_R^j \, H}$$

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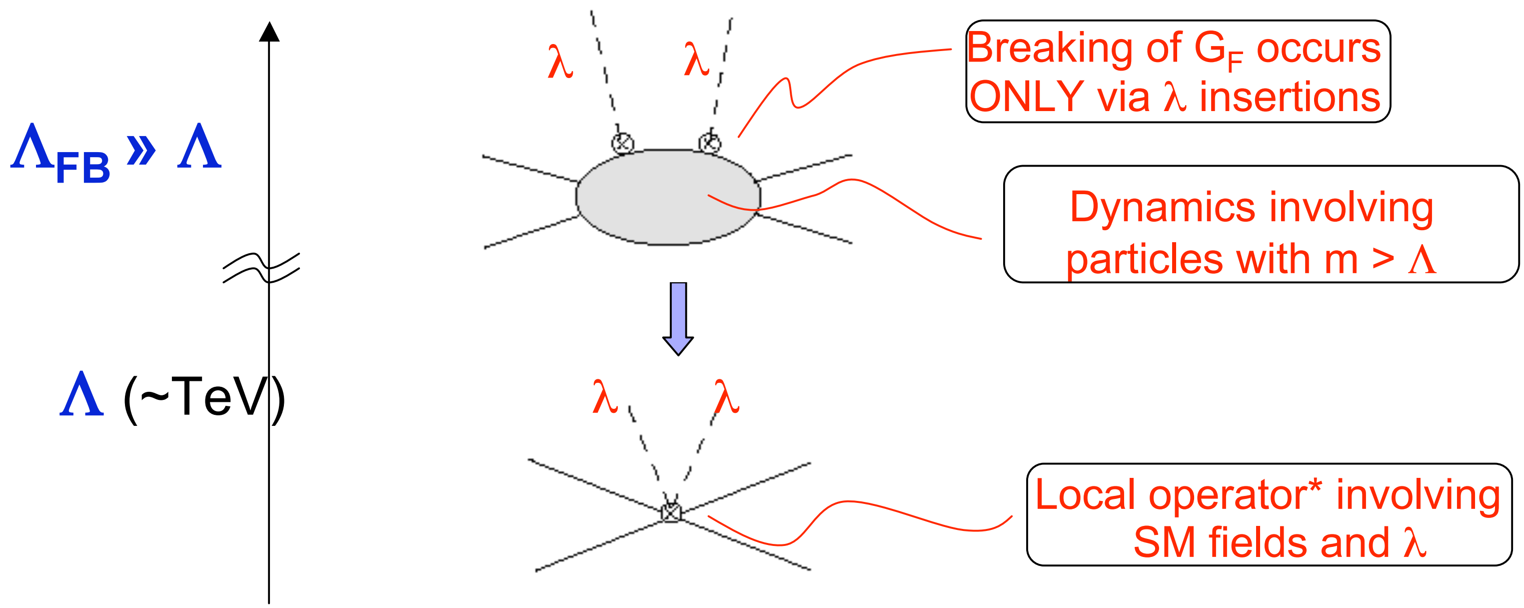
- $O_n^{(d)}$: most conservative guess is Minimal Flavor Violation Hypothesis:
  "The only sources of G_F-breaking are proportional to the mass matrices: λ_U , λ_D , λ_e , ..."

  - Can be implemented in explicit models (SUSY, technicolor, extra-dims)
  - Can be formulated in EFT language (insensitive to model details)

MFV and effective theory



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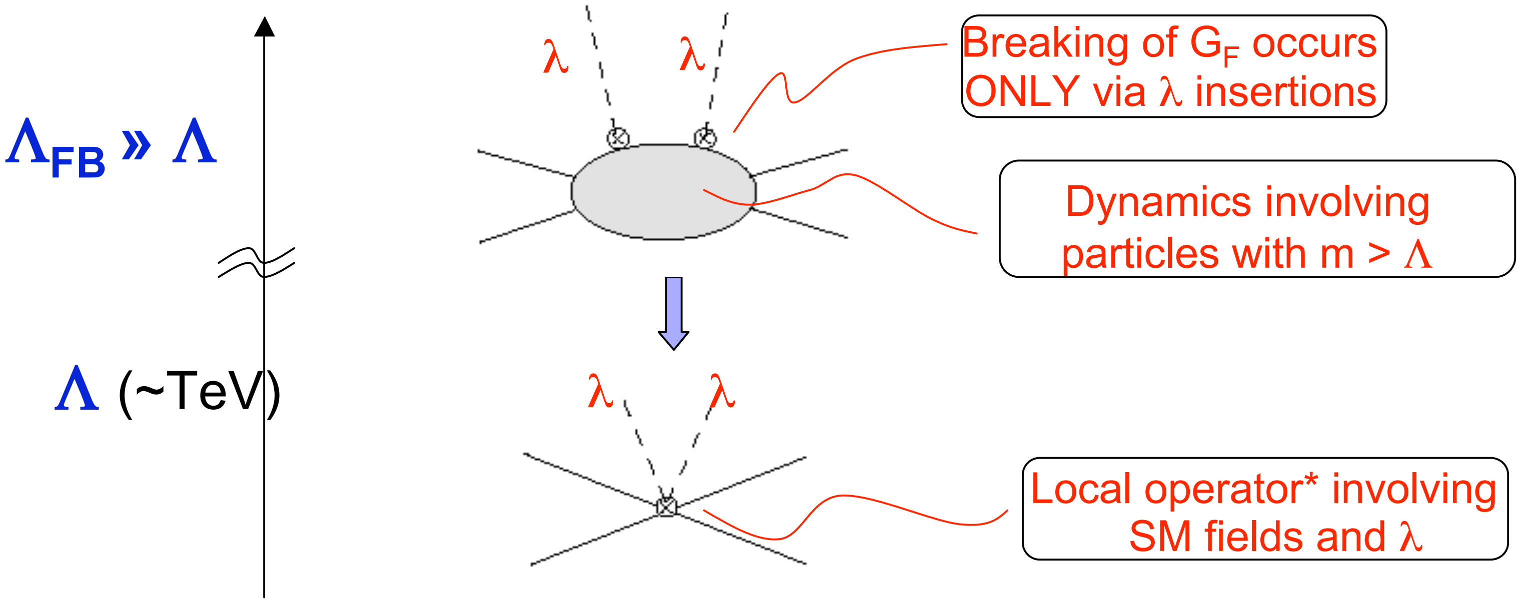
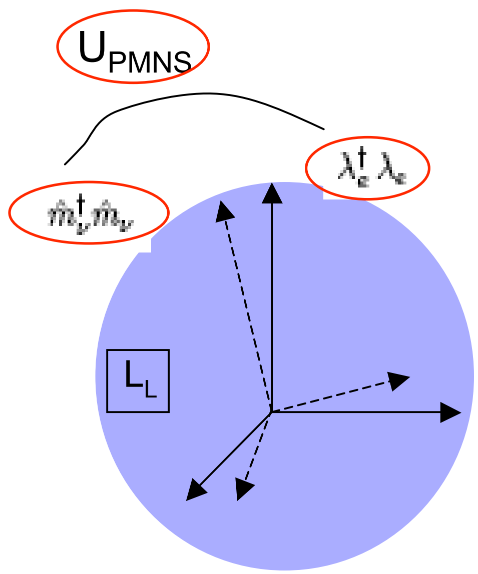


Rules of the game:

1. Identify flavor symmetry group G_F
2. Identify sources of symmetry breaking (λ) and their properties as spurions
3. Construct local operators [SM fields and λ] formally invariant under G_F

MFV hypothesis in the lepton sector

- m_ν and m_l select two distinct eigen-bases in L_L space (related by U_{PMNS})



$$L_L^i = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}^i$$

i=1,2,3

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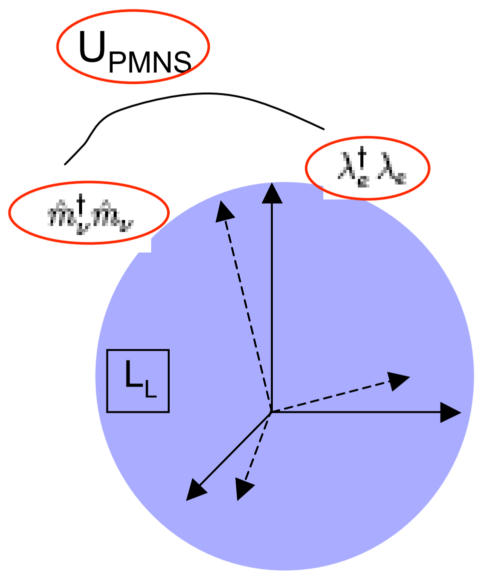

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- MFV(ℓ): BSM flavor structures are aligned with m_ν and m_l in L_L space

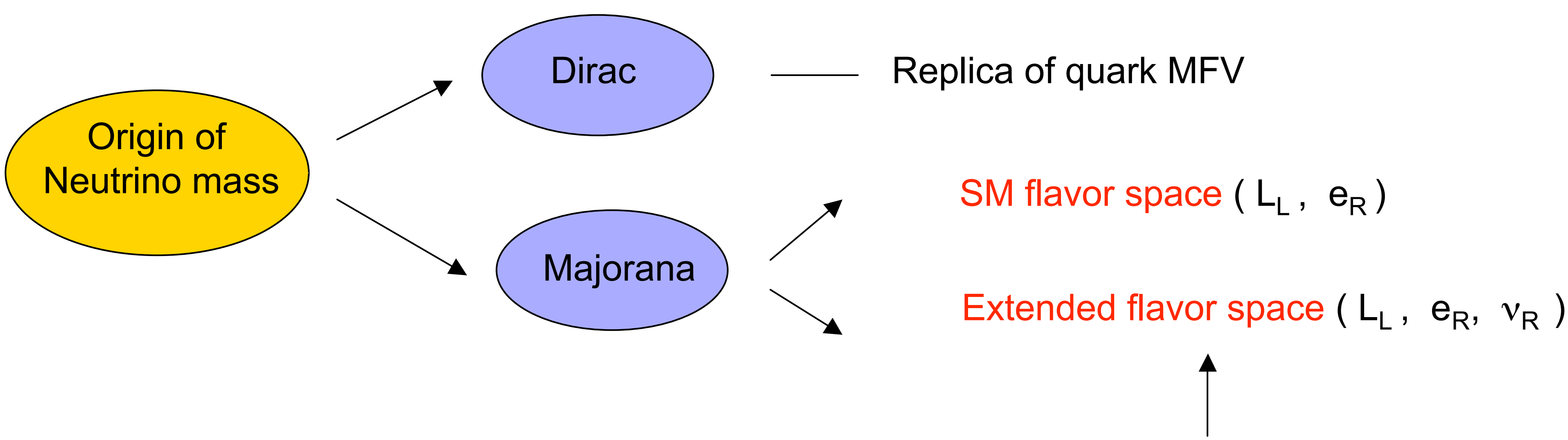
  [$\rightarrow$ FCNC are controlled by masses and U_{PMNS}]

1. Is leptonic "flavor problem" solved ?
2. What are the experimental signatures ?
3. Can we have leptogenesis ?

- MFV in the lepton sector defines a constrained class of models, with distinct phenomenological signatures

Model-independent tool to investigate sources of flavor breaking

- Even with our restrictive definition, several options are available:

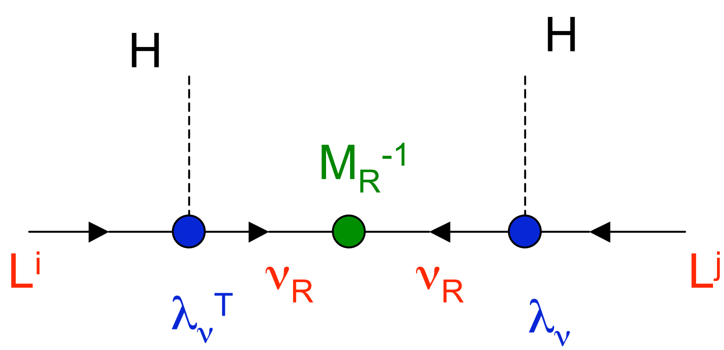


IN THIS TALK I FOCUS ON THIS REALIZATION

MFV in models with heavy ν_R

- Spurions in L_L space: $\lambda_e^\dagger \lambda_e$ $\lambda_\nu^\dagger \lambda_\nu$ $g_\nu^\dagger g_\nu = \lambda_\nu^\dagger \hat{M}_R^{-1} \lambda_\nu^* \lambda_\nu^T \hat{M}_R^{-1} \lambda_\nu$

$\boxed{m_\nu \sim v^2/M_\nu\ g_\nu}$



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$m_\nu \sim v^2/M_\nu\ g_\nu$

- Strict MFV definition (alignment of $\lambda_\nu^\dagger \lambda_\nu$ and $g_\nu^\dagger g_\nu$) $\Rightarrow$

$$\boxed{\hat{M}_R = I \qquad \lambda_\nu = \lambda_\nu^*}$$

Highly predictive, but excludes possibility of CP violation in R-handed sector !

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Highly predictive, but excludes possibility of CP violation in R-handed sector !

- Lift the requirement $\boxed{\lambda_\nu = \lambda_\nu^*}$

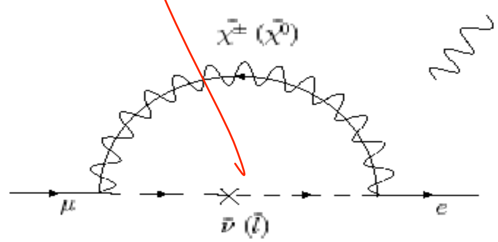
  - scenario similar to quark MFV: flavor broken only by Yukawas (λ_e , λ_ν)
  - now have three distinct flavor-breaking structures in L_L flavor space

Phenomenology of $\ell_i \to \ell_j \gamma$

- Effective coupling governing $\ell_i \to \ell_j$ transitions: $\boxed{\Delta_{\rm FC} = \lambda_\nu^\dagger \lambda_\nu}$

$$\boxed{H_{\rm eff} = \frac{C_L}{\Lambda^2}\, H^\dagger\, \bar{e}_R^i\, \sigma^{\mu\nu}\, (\lambda_e\, \Delta_{\rm FC})^{ij}\; L_L^j\; F_{\mu\nu} + \ldots}$$

~ TeV



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Mass-scale of R-handed ν

Orthogonal & hermitian matrix
containing CP violating phases

Observed neutrino
mass and mixing matrix

$$H = e^{i\,\Phi} \qquad \Phi = \begin{pmatrix} 0 & \phi_1 & \phi_2 \\ -\phi_1 & 0 & \phi_3 \\ -\phi_2 & -\phi_3 & 0 \end{pmatrix}$$

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- Direct link to neutrino phenomenology lost unless *H*=I (CP limit)

- However, H contains the CPV phases controlling leptogenesis → explore correlations between successful leptogenesis and FCNC

$$\boxed{\Delta_{\rm FC} \equiv \lambda_\nu^\dagger \lambda_\nu = \frac{M_\nu}{v^2} U_{\rm PMNS} \, \hat{m}_\nu^{1/2} \, H^2 \, \hat{m}_\nu^{1/2} \, U_{\rm PMNS}^\dagger} \longleftrightarrow \boxed{\Delta_{CP} \equiv \lambda_\nu \lambda_\nu^\dagger = \frac{M_\nu}{v^2} H \, \hat{m}_\nu \, H}$$

Phenomenology of $\ell_i \to \ell_j\gamma$ (CP limit)

$$B_{\ell_i \to \ell_j \gamma} = \frac{v^2 M_\nu^2}{\Lambda^4} \times |b_{ij}(U_{\rm PMNS}; m_{\rm min}; \Delta m_\nu^2)|^2 \times |c_{RL}^{(1-2)}|^2 \, I_{PS}$$

Investigate: (i) overall normalization and

(ii) MFV signatures $\longleftrightarrow$ $b_{ij} = (U \frac{m_\nu}{v_{ew}} U^T)_{ij}$

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ia) Flavor problem “solved” for $M_\nu < 10^{12\text{-}13}$ GeV (normalization of g_ν and λ_ν)

ib) Signals within reach of future facilities are expected only for large hierarchy between scale of $U(1)_{LN}$ breaking and Λ

$$\boxed{B_{\mu \to e(\gamma)} \sim 10^{-13} \quad \underset{c_i \sim O(1)}{\Leftrightarrow} \quad M_\nu \sim 10^{12}\,\mathrm{GeV} \times (\Lambda/10\,\mathrm{TeV})^2}$$

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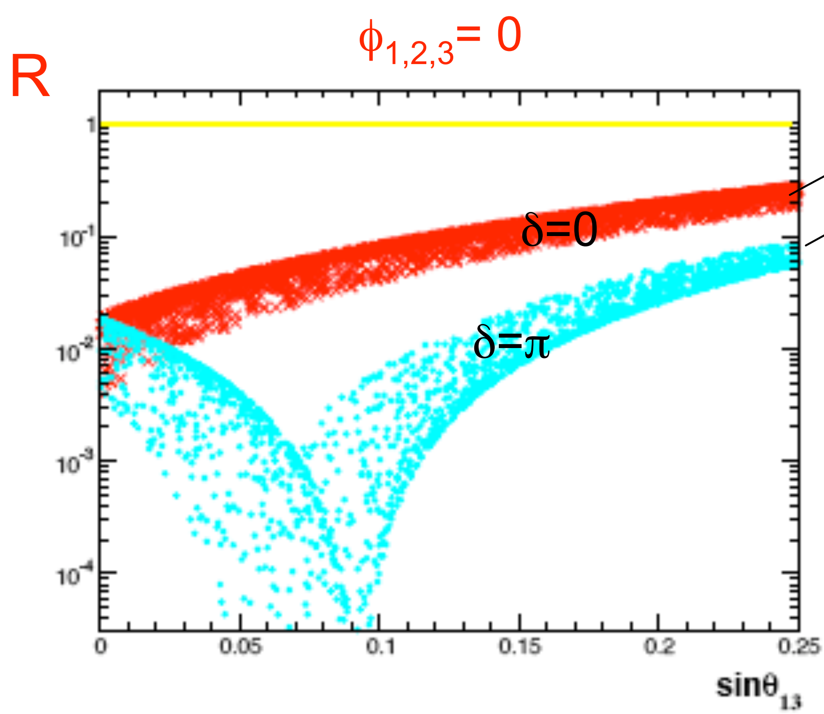
ii) MLFV *predicts* ratios of $B(\ell_a\to\ell_b\gamma)$ (c_{RL} and Λ cancel out) in terms of U_{PMNS} and mass splittings with pattern:

$$\boxed{B(\tau\to\mu\gamma) >> B(\tau\to e\gamma) \sim B(\mu\to e\gamma)}$$

(with $\mu\to e/\tau\to\mu$ suppression increasing as $s_{13} \to 0$)

Illustration: R= B($\mu \to e\,\gamma$)/B($\tau \to \mu\gamma$)



Pattern entirely determined by:

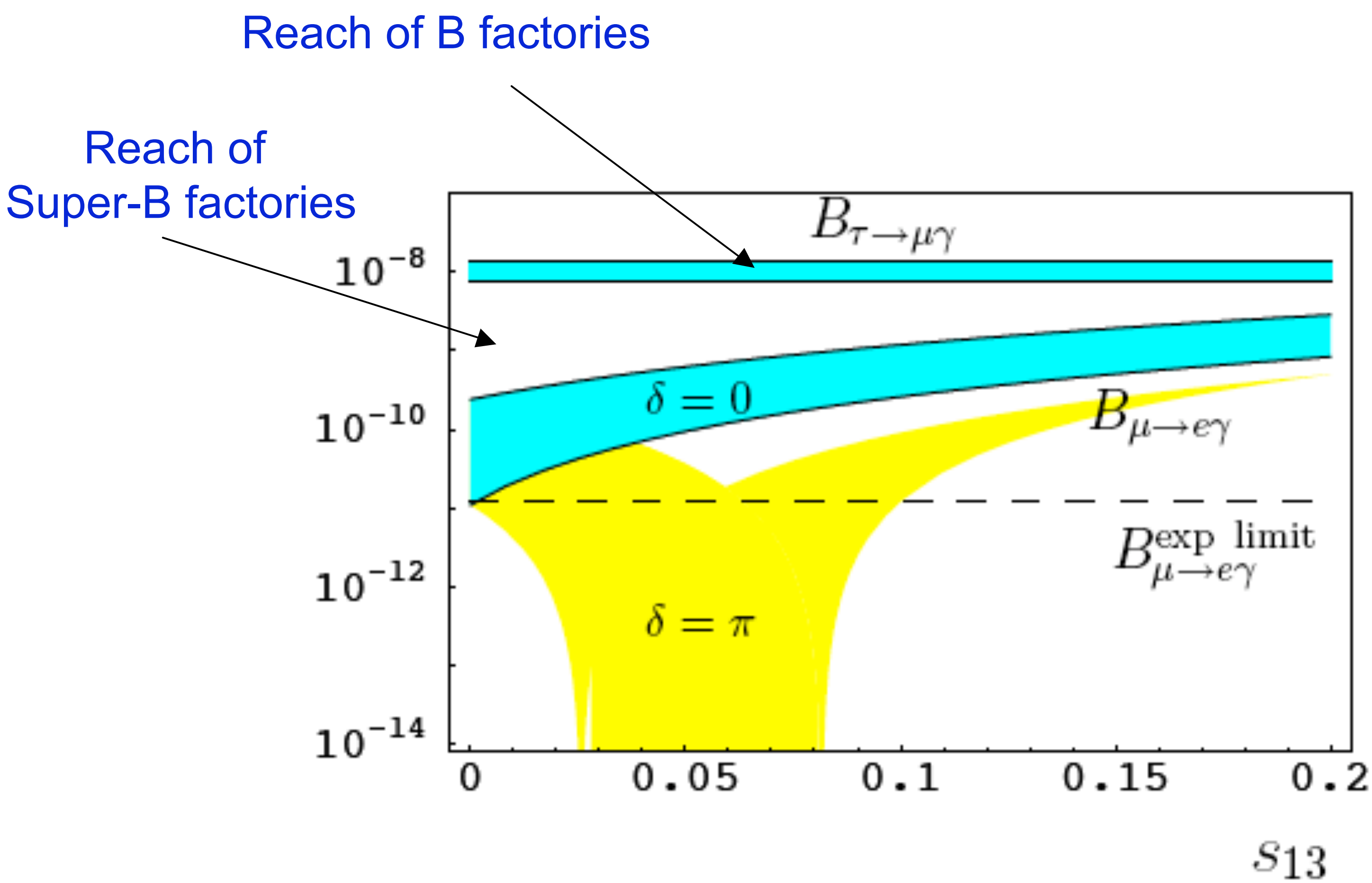
- Δm^2_{atm} >> Δm^2_{sol}
- θ_{atm} , θ_{sol} >> θ_{13}

$\updownarrow$

$$b_{ij} = (U \frac{m_\nu}{v_{ew}} U^T)_{ij}$$

This framework can be tested !

- If $s_{13} \geq 0.08$, limits on $B(\tau \to \mu\gamma)$ preclude observing $\tau \to \mu\gamma$ at B factories
- If $\tau \to \mu\gamma$ is observed at B factories then $s_{13} < 0.08$



MFV with CP violation

- So far I discussed phenomenology in the limit of CP symmetry (reduced number of parameters, allowing for predictive power!)

- Now lift the assumption of CP and investigate:

1. Viability of thermal leptogenesis if the only sources of flavor breaking are λ_e *and* λ_ν (non trivial by itself)

2. Leptogenesis constraints on λ_ν and M_ν and impact on FCNC

   - Is the framework predictive?
   - Do we learn something about overall rate and relative strength of $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$?

Leptogenesis with MFV

Leptogenesis accounts for $\eta_B = \dfrac{n_B - n_B}{n_\gamma} = (6.3 \pm 0.3) \times 10^{-10}$ through:

- Out of equilibrium decays of N_i in presence of CPV $\Rightarrow n_L \neq 0$
- EW sphalerons (B+L violation) convert $n_L \leftrightarrow n_B$

$$\boxed{\eta_B = \frac{a_{sph}}{n_\gamma} \sum_i \varepsilon_i \times d_i \quad + \quad \ldots}$$

$\boxed{a_{sph}}$ O(1) factor governing conversion $n_L \leftrightarrow n_B$

$\boxed{d_i}$ Fraction of N_i decaying out of equilibrium (from solution of appropriate Boltzmann Eqs)

$\boxed{\varepsilon_i}$ CP asymmetry

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No detailed input on UV physics

$\downarrow$

O(1) uncertainty

$\boxed{a_{sph}}$ O(1) factor governing conversion $n_L \leftrightarrow n_B$

$\boxed{d_i}$ Fraction of N_i decaying out of equilibrium (from solution of appropriate Boltzmann Eqs)

$\boxed{\varepsilon_i}$ CP asymmetry

- A number of questions can be addressed without reference to UV details:

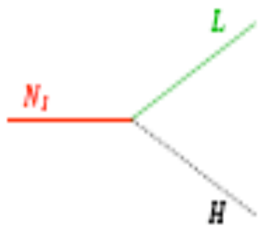
  a) Structure of CP asymmetries in ν_R decays into H + L_L

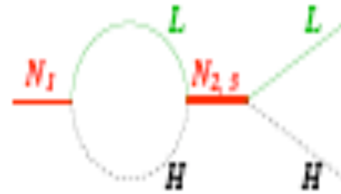
  b) Structure of radiatively induced ν_R mass splitting

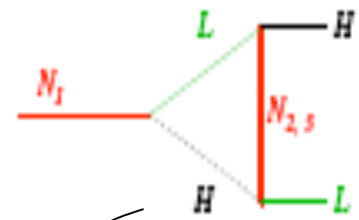
  c) Is there enough CP violation for leptogenesis, *in principle* ?
  (find non-zero CP violating weak-basis invariants)

- Within SM + ν_R particle content, we can perform numerical estimates, to understand gross features of FCNC under successful leptogenesis

a) CP asymmetries in ν_R decays

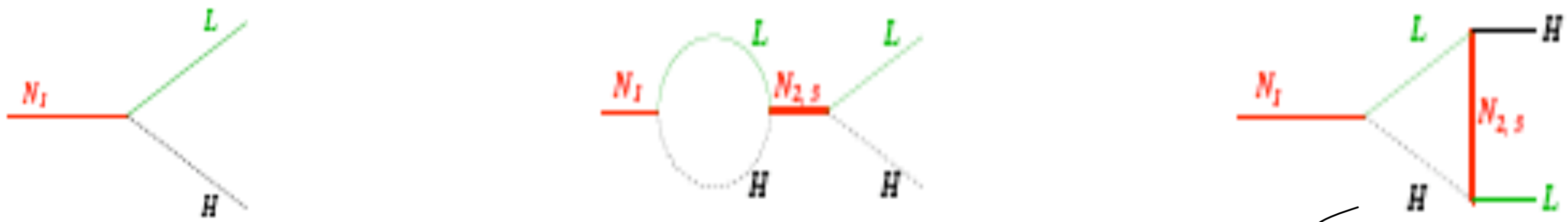






$$\epsilon_i \equiv \frac{\sum_k [\Gamma(N_i \to l_k H^*) - \Gamma(N_i \to \bar{l}_k H)]}{\sum_k [\Gamma(N_i \to l_k H^*) + \Gamma(N_i \to \bar{l}_k H)]} = -\sum_{j \neq i} \frac{3}{2} \frac{M_i}{M_j} \frac{\Gamma_j}{M_j} I_j \frac{2S_j + V_j}{3}$$

a) CP asymmetries in ν_R decays



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$$I_j = \frac{\mathrm{Im}\left[(\bar{\lambda}_\nu \bar{\lambda}_\nu^\dagger)^2_{ij}\right]}{|\bar{\lambda}_\nu \bar{\lambda}_\nu^\dagger|_{ii} |\bar{\lambda}_\nu \bar{\lambda}_\nu^\dagger|_{jj}} \qquad \frac{\Gamma_j}{M_j} = \frac{|\bar{\lambda}_\nu \bar{\lambda}_\nu^\dagger|_{jj}}{8\pi}$$

$$S_j = \frac{M_j^2 (M_j^2 - M_i^2)}{(M_j^2 - M_i^2)^2 + M_i^2 \Gamma_j^2}$$

$S_j \gg V_j$ if $\Delta M_R \sim \Gamma$

$\bar{\lambda}_\nu$: Yukawa in the basis where M_R is diagonal with eigenvalues $M_{1,2,3}$

b) ν_R mass splitting induced according to MLFV

$$M_R = M_R^{(0)} + \sum c_n \, \delta M_R^{(n)}$$

$$(M_R^{(0)})_{ij} = M_\nu \, \delta_{ij}$$

Combinations of Yukawas allowed by MFV

$$\boxed{\begin{aligned}
\delta M_R^{(11)} &= M_\nu \left[\lambda_\nu \lambda_\nu^\dagger + (\lambda_\nu \lambda_\nu^\dagger)^T\right] \,, \\
\delta M_R^{(21)} &= M_\nu \left[\lambda_\nu \lambda_\nu^\dagger \lambda_\nu \lambda_\nu^\dagger + (\lambda_\nu \lambda_\nu^\dagger \lambda_\nu \lambda_\nu^\dagger)^T\right] \,, \\
\delta M_R^{(22)} &= M_\nu \left[\lambda_\nu \lambda_\nu^\dagger (\lambda_\nu \lambda_\nu^\dagger)^T\right] \,, \\
\delta M_R^{(23)} &= M_\nu \left[(\lambda_\nu \lambda_\nu^\dagger)^T \lambda_\nu \lambda_\nu^\dagger\right] \,, \\
\delta M_R^{(24)} &= M_\nu \left[\lambda_\nu \lambda_e^\dagger \lambda_e \lambda_\nu^\dagger + (\lambda_\nu \lambda_e^\dagger \lambda_e \lambda_\nu^\dagger)^T\right] \,, \\
\delta M_R^{(31)} &= \ldots.
\end{aligned}}$$

Perturbative regime $\Rightarrow$ $c_{11} \sim g_{\rm eff}^2/(4\pi)^2, \; c_{2i} \sim c_{11}^2, \ldots$

Strongly-interacting regime $\Rightarrow$ all $c_n \sim \mathcal{O}(1)$

c) Is there enough CP violation for leptogenesis, *in principle* ?

- Yukawa sector: six independent physical CPV phases (three if $\lambda_e = 0$)
- Can be characterized in terms of weak-basis invariants (insensitive to changes of basis or re-phasing of the fields). Simplest invariants:

Branco-Morozumi-Nobre-Rebelo 2001

M_R generic mass term

$$h_\nu \equiv \lambda_\nu \lambda_\nu^\dagger$$

$$\boxed{\begin{aligned} B_1 &\equiv \mathrm{Im\,Tr}\left[h_\nu\,(M_R^\dagger M_R) M_R^* h_\nu^* M_R\right] \\ B_2 &\equiv \mathrm{Im\,Tr}\left[h_\nu\,(M_R^\dagger M_R)^2 M_R^* h_\nu^* M_R\right] \\ B_3 &\equiv \mathrm{Im\,Tr}\left[h_\nu\,(M_R^\dagger M_R)^2 M_R^* h_\nu^* M_R (M_R^\dagger M_R)\right] \end{aligned}}$$

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Simple correspondence to leptogenesis asymmetries

$$B_1 = M_1 M_2 (M_2^2 - M_1^2) \boxed{\mathrm{Im}\left((\bar\lambda_\nu \bar\lambda_\nu^\dagger)_{12}^2\right)} + \ (2\leftrightarrow 3) + (1\leftrightarrow 3)$$

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- $B_i \neq 0$ if use any of the $\delta M_R^{(2n)}$ splittings (quartic in the Yukawa!)

- Parameter space scan:

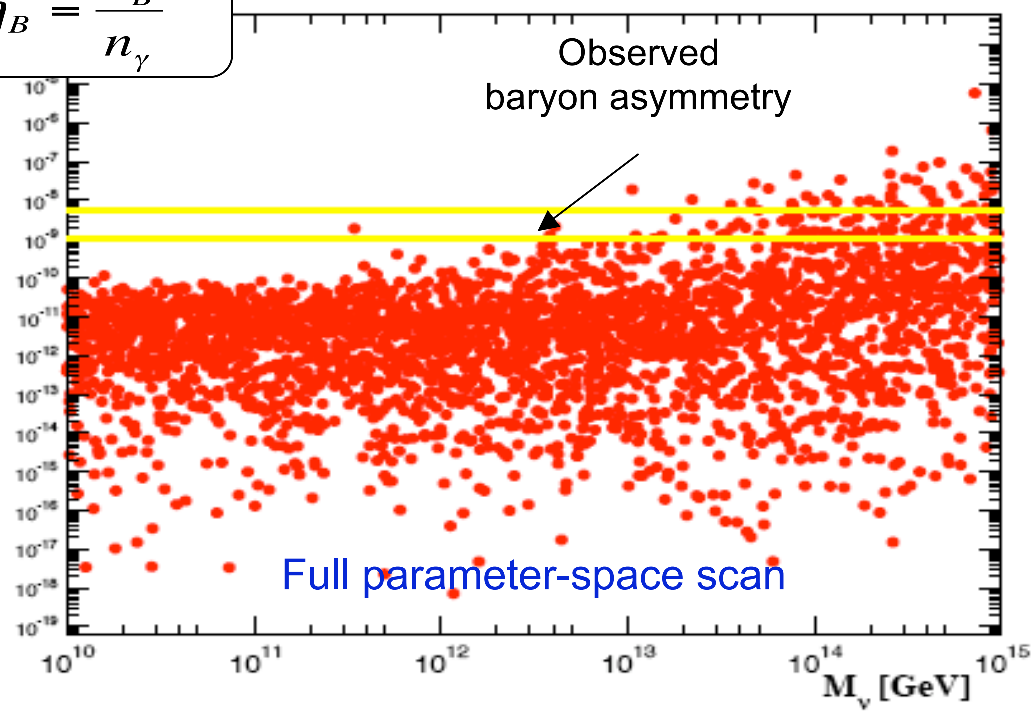
- δM_R : flavor structures; size of coefficients: $c \in [10^{-4}, 1]$
- $M_\nu \in [10^5, 10^{15}]$ GeV
- $\phi_{1,2,3} \in [0.001, 1]$
- $m_\nu^{min} \in [10^{-4}, 0.6]$ eV
- $\theta_{13} \in [0^o, 15^o]$

- Leptogenesis highlights:

- Leptogenesis is possible in MFV ! ("Radiative resonant leptogenesis")

- Key feature: high values of $M_\nu > 10^{12}$ GeV and $|\phi_{1,2,3}| \geq 0.01$ preferred (due to scaling of CP asymmetries with $\lambda_\nu \propto M_\nu^{1/2}$)

$$\eta_B = \frac{n_B}{n_\gamma}$$



- Impact on FCNC

$$\boxed{B_{\ell_i \to \ell_j \gamma} = \frac{v^2 M_\nu^2}{\Lambda^4} \times |b_{ij}(U_{\mathrm{PMNS}}; m_{\mathrm{min}}; \phi_i)|^2 \times |c_{RL}^{(1-2)}|^2 \, I_{PS}}$$

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1) $B_{i,LFV} \propto M_\nu^2$ $\Rightarrow$ high values of M_ν increase FCNC rates.

If $\Lambda \sim$ 1-10 TeV, this scenario $\Rightarrow$ signal for MEG ($\mu \to e \gamma$ @ 10^{-13} level)

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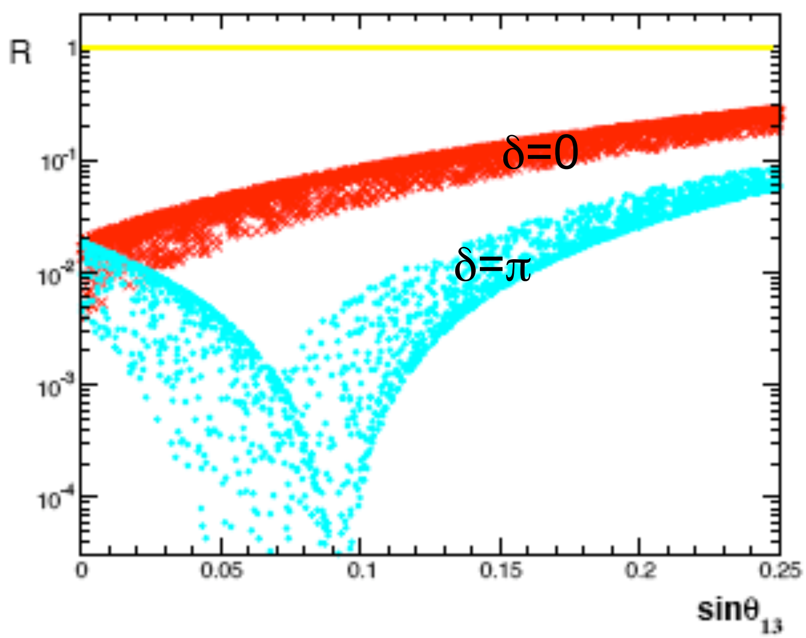
$\phi_{1,2,3} = 0$



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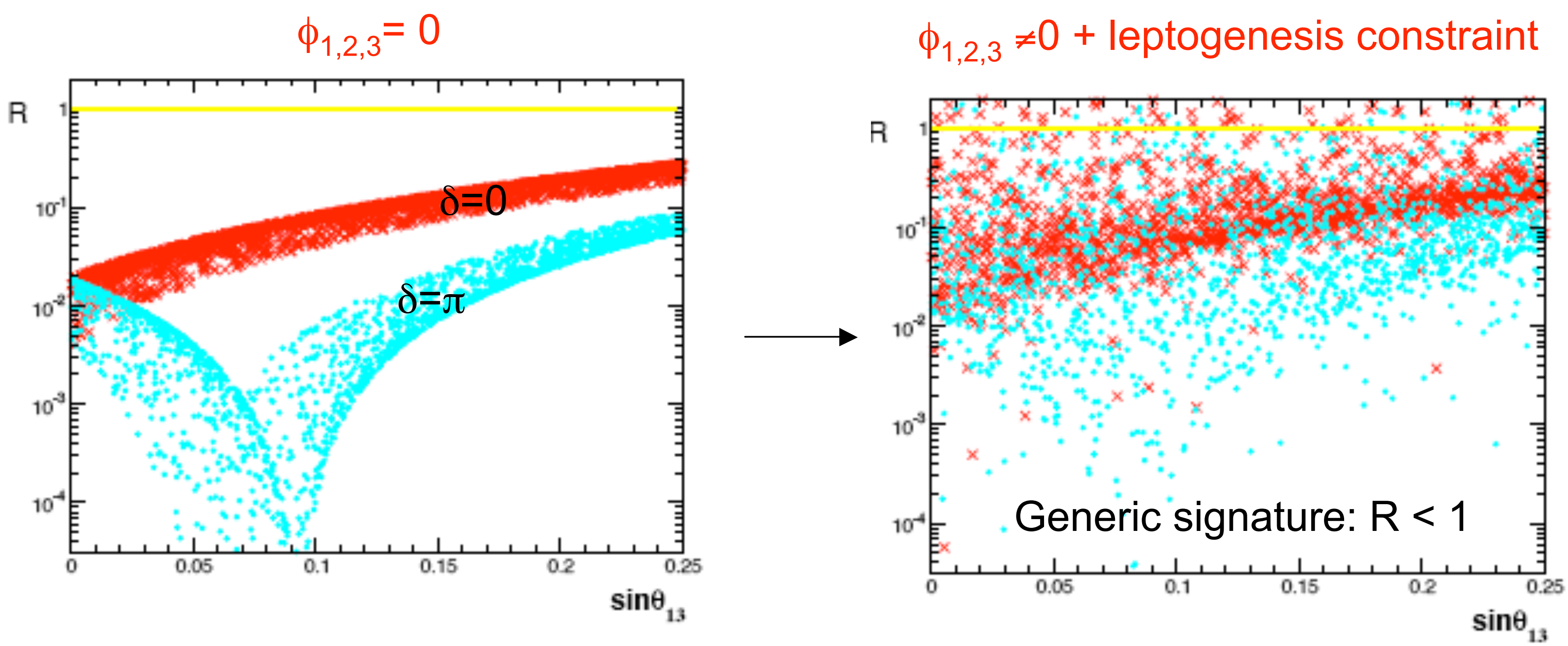
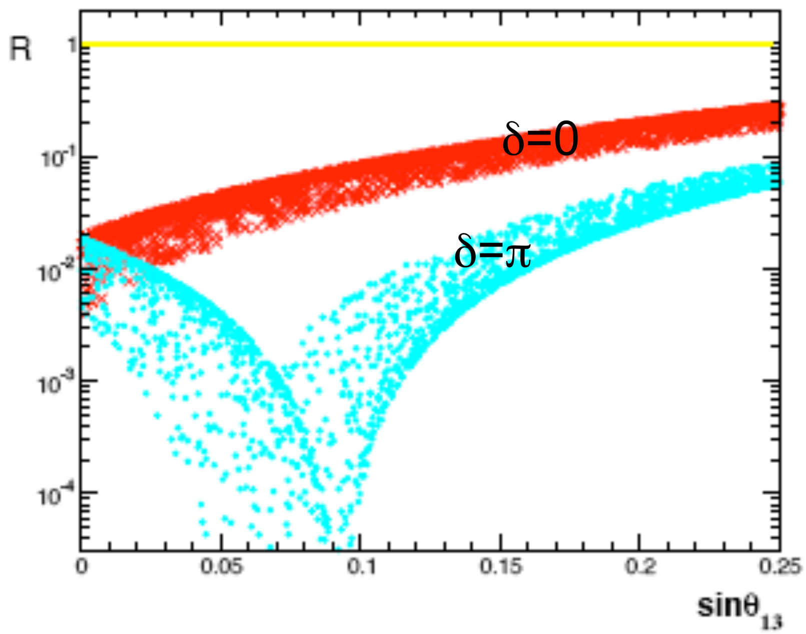
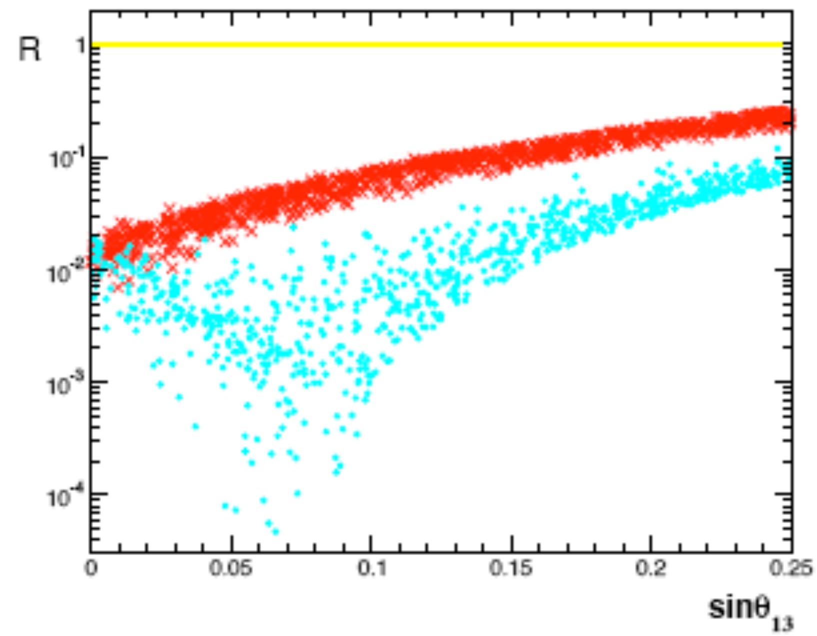


3) However there is a "small phase regime" (M_ν > 10^{14} GeV) with successful leptogenesis & typical PMNS-induced pattern

$\phi_{1,2,3}$= 0



| $\phi_{1,2,3}$ |< 0.1 + leptogenesis constraint



“Hot” recent developments and their impact on MFV-leptogenesis

Flavor Effects in Leptogenesis

Abada, Davidson, Josse-Michaoux, Losada, Riotto '06 Nardi, Nir, Roulet, Racker '06

- At $T < T_{fl}$, interactions mediated by Yukawa couplings come in equilibrium
  $\Rightarrow$ project lepton asymmetry onto individual flavors

$$N_1 \rightarrow \ell_1 \, H^*$$
$$\ell_1 \rightarrow \ell_{\tau,\mu,e}$$

$T_\tau \sim 10^{12}$ GeV

$T_\mu \sim 10^9$ GeV

$$\Gamma_\alpha \sim 10^{-3} \, \lambda_\alpha^2 \; T$$

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$$\Delta_\alpha \equiv B/2 - L_\alpha$$

$$\begin{aligned}\frac{dN_{N_1}}{dz} &= -D\left(N_{N_1} - N_{N_1}^{\rm eq}\right) \\ \frac{dN_{B-L}}{dz} &= \varepsilon_1 D\left(N_{N_1} - N_{N_1}^{\rm eq}\right) - W_1^{\rm ID} N_{B-L}\end{aligned} \quad \longrightarrow \quad \begin{aligned}\frac{dN_{N_1}}{dz} &= -D\left(N_{N_1} - N_{N_1}^{\rm eq}\right) \\ \frac{dN_{\Delta_\alpha}}{dz} &= \varepsilon_{1\alpha} D\left(N_{N_1} - N_{N_1}^{\rm eq}\right) - P_{1\alpha}^0 W_1^{\rm ID} N_{\Delta_\alpha}\end{aligned}$$

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- Key consequences:
  - CP asymmetries are sensitive to CPV phases of U_{PMNS}
  - Washout via inverse decays is less effective

Memory Effects in Leptogenesis

De Simone - Riotto '07

- Quantum Boltzmann eqs: "collision" term depends on history of the system

$$\frac{\partial n_{\mathcal{L}_i}(X)}{\partial t} = -\int d^3z \int_0^t dt_z \, \mathrm{Tr}\left[\Sigma^{>}_{\ell_i}(X,z)G^{<}_{\ell_i}(z,X) - G^{>}_{\ell_i}(X,z)\Sigma^{<}_{\ell_i}(z,X)\right.$$
$$\left. + G^{<}_{\ell_i}(X,z)\Sigma^{>}_{\ell_i}(z,X) - \Sigma^{<}_{\ell_i}(X,z)G^{>}_{\ell_i}(z,X)\right].$$

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- Important consequence:
  - CP asymmetries depend on $z=M_1/T$ (time variable)

$$\varepsilon_1(z) = \varepsilon_1^{(0)}\left[2\sin^2\left(\boxed{\frac{(M_2-M_1)z^2}{4H(M_1)}}\right) - \frac{\Gamma_2}{M_2-M_1}\sin\left(\frac{(M_2-M_1)z^2}{2H(M_1)}\right)\right]$$

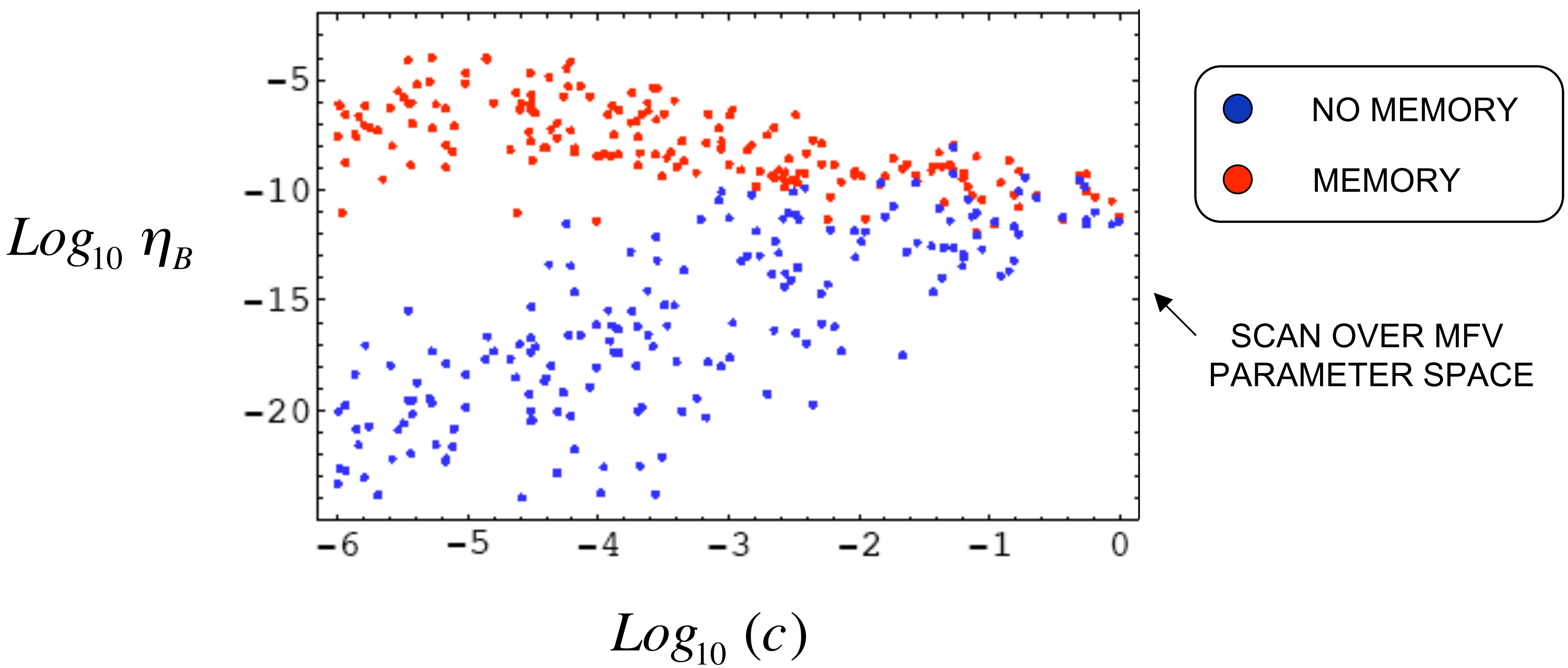
  - Effect is important if $1/\Delta M_{12} > 1/\Gamma_N \sim 1/H\ (T=M_1)$

Impact on MFV-leptogenesis

VC-DeSimone-Isidori-Masina-Riotto, in progress

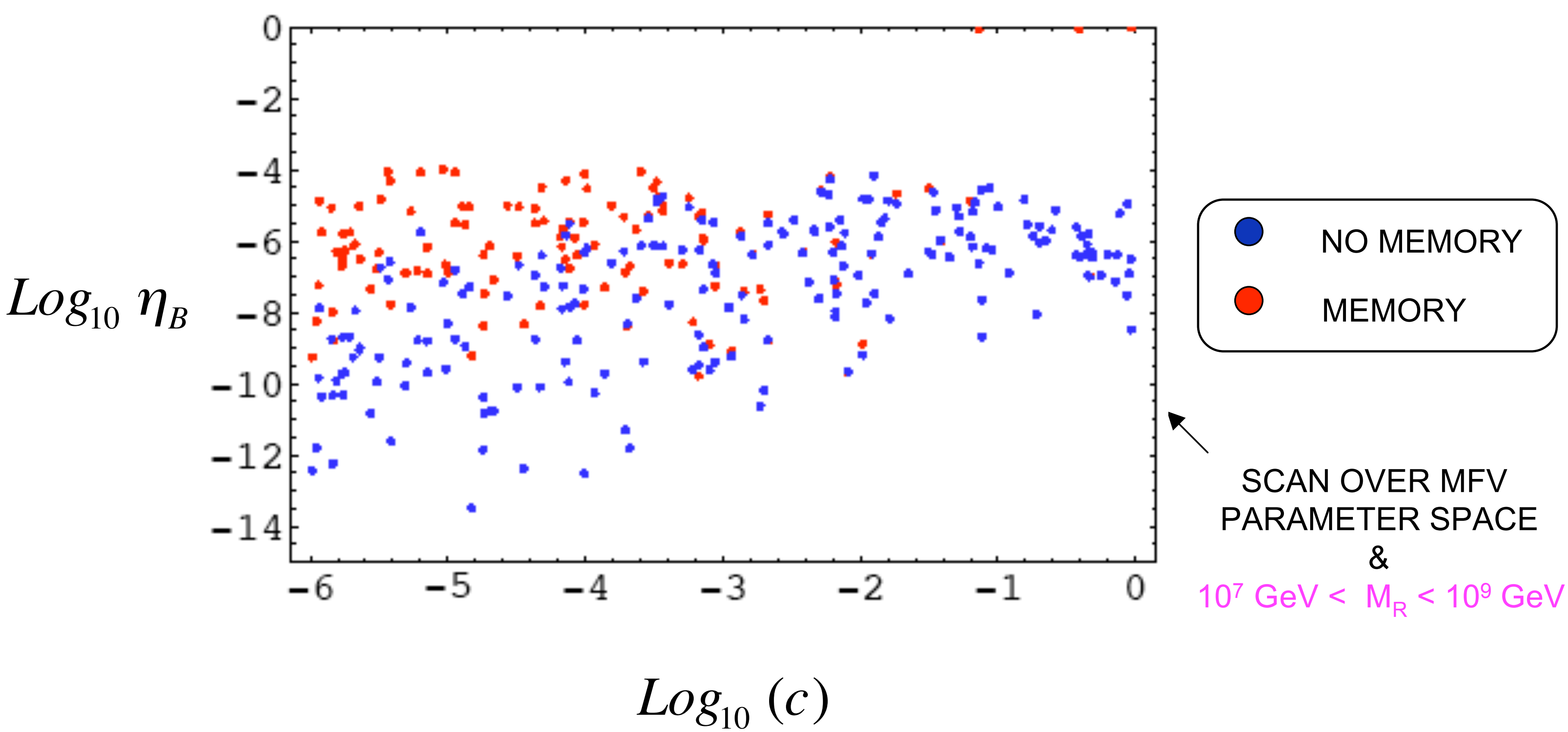
- Flavor effects imply need to study several $T \sim M_R$ regimes:

1. Unflavored regime: $M_R > 10^{12}$ GeV
   "Memory" effects are controlled by parameter "c" $\leftrightarrow$ $\Delta M_R/\Gamma$



2. Fully flavored regime: $M_R < 10^9$ GeV

- Larger values of BAU (less washout)
- "Memory" effects again mainly controlled by "c" $\leftrightarrow$ $\Delta M_R/\Gamma$



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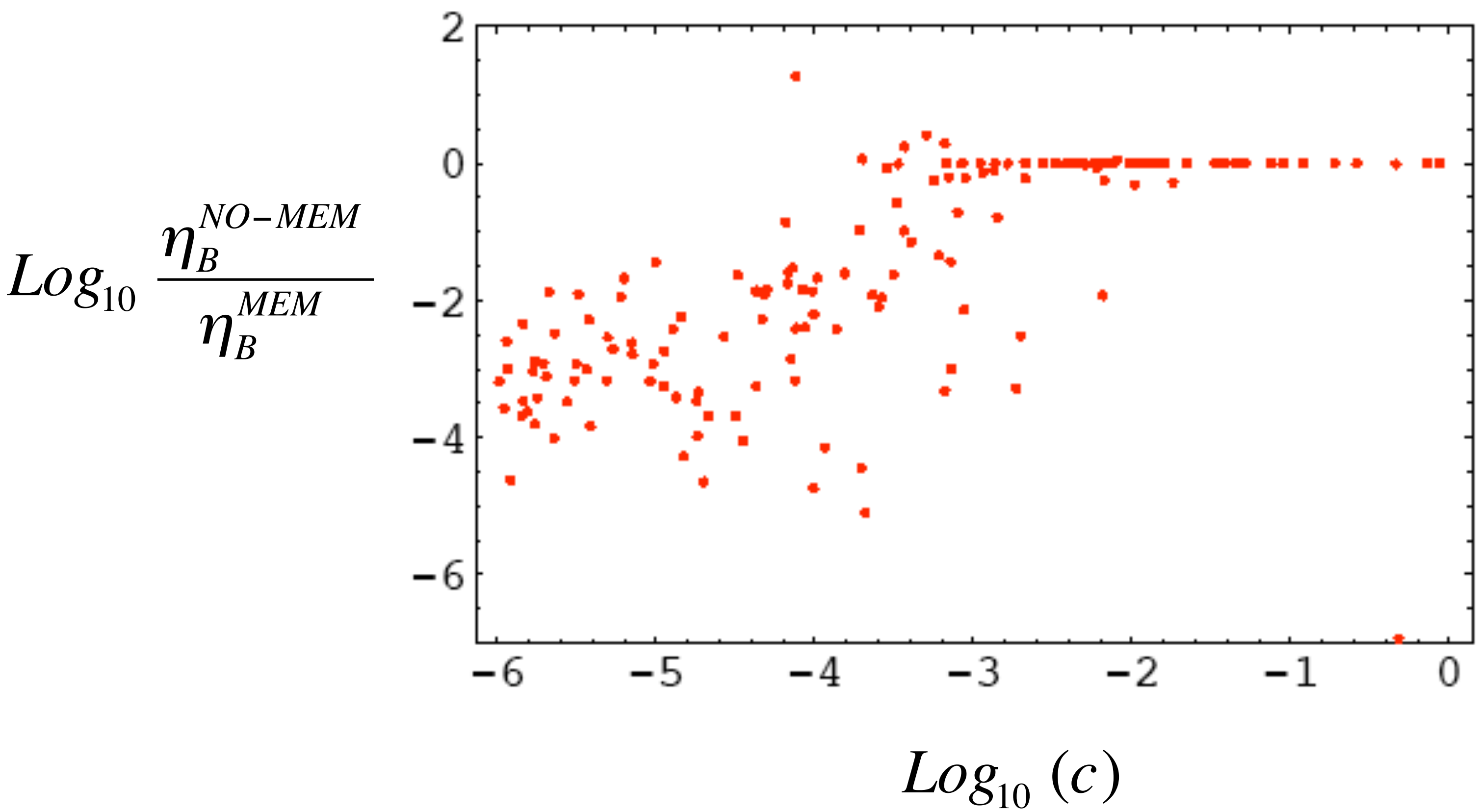
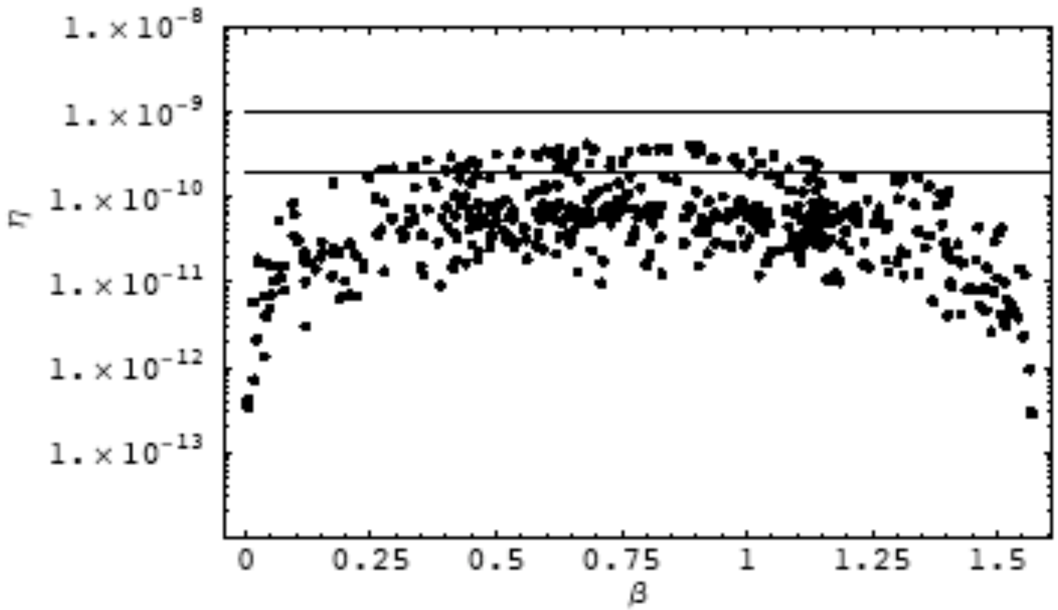


- Possibility of leptogenesis with exclusively low-energy CP violation



$M_\nu < 10^9$ GeV: three-flavor case

Figure 5: The baryon asymmetry η_B with the Majorana phase β being the only source of CP violation.

Summary

- The see-saw scenario provides a unified framework to account for the origin of neutrino masses, baryon asymmetry and lepton flavor violation. It is of great interest to study its low-energy footprints.

- Within the context of Minimal Flavor Violation with heavy ν_R , correlations emerge among successful leptogenesis and low-energy observables:

  - Leptogenesis is viable, in principle and in practice, with moderate-sized phases ($|\phi_{1,2,3}| \geq 0.01$) and high R-handed scale ($M_\nu > 10^{12}$ GeV)

  - Implications for FCNC:
    - If $\Lambda \sim$ 1-10 TeV, then $\mu \to e\gamma$ is well within the reach of MEG
    - For $M_\nu > 10^{14}$ GeV, FCNC pattern is fully determined by U_{PMNS} and Δm_ν^2

- Flavor and memory produce in this scenario new effects currently under investigation

Additional Material

How does it work for quarks ?

- $\boxed{G_{\rm QF} = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}}$ broken only by λ_U ~$(3,\bar{3},1)$ *and* λ_D~$(3,1,\bar{3})$

- Typical MFV operator mediating FCNC:

D'Ambrosio et al 2002

$$O_{F1} = H^\dagger\ \bar{D}_R\, \sigma^{\mu\nu} \left(\lambda_D\, \lambda_U \lambda_U^\dagger\right) Q_L\ F_{\mu\nu} \longrightarrow\ \bar{d}_R^{i'}\, \sigma^{\mu\nu}\ m_D^i \Delta_{FC}^{ij}\ d_L^{j'}\ F_{\mu\nu}$$

$$\boxed{(\Delta_{FC})_{ij} = (\lambda_U \lambda_U^\dagger)_{ij} \simeq \left(\frac{m_t}{v}\right)^2\ V_{3i}^*\, V_{3j}}$$

Normalization

Mixing pattern

1. FCNC suppression follows from Cabibbo hierarchy (despite $m_t >> m_{c,u}$)
   Flavor problem essentially "solved": Λ ~ TeV is now allowed

2. Highly predictive (=testable) framework, relates various $d_i \rightarrow d_j$ transitions.
   Tool to investigate structure of flavor-breaking. Far from being verified.

MLFV: minimal field content

- $G_{\rm LF} = SU(3)_{L_L} \times SU(3)_{E_R}$ broken only by $\lambda_e \; , \; g_\nu$

$$\boxed{\mathcal{L}_{\rm Sym.Br.} = -\lambda_e^{ij}\, \bar{e}_R^i (H^\dagger L_L^j) - \frac{1}{2\Lambda_{\rm LN}}\, g_\nu^{ij} (\bar{L}_L^{ci} \tau_2 H)(H^T \tau_2 L_L^j)}$$

Formally invariant under $\boxed{\begin{array}{l} L_L \to V_L\, L_L \\ e_R \to V_R\, e_R \end{array}}$ if $\boxed{\begin{array}{l} \lambda_e \to V_R\, \lambda_e V_L^\dagger \\ g_\nu \to V_L^*\;\, g_\nu V_L^\dagger \end{array}}$

- Independent spurions in L_L space: $\lambda_e^\dagger \lambda_e \quad , \quad g_\nu^\dagger g_\nu$

MLFV: extended field content

- $\bar{G}_{\rm LF} = SU(3)_{L_L} \times SU(3)_{E_R} \times O(3)_{\nu_R}$ broken only by λ_e , λ_ν

$$\boxed{\mathcal{L}_{\rm Sym.Br.} = -\lambda_e^{ij}\, \bar{e}_R^i (H^\dagger L_L^j) + i\lambda_\nu^{ij} \bar{\nu}_R^i (H^T \tau_2 L_L^j) + {\rm h.c.}}$$

Formally invariant under $\boxed{\begin{array}{l} L_L \to V_L\, L_L \\ e_R \to V_R\, e_R \\ \nu_R \to O_\nu\, \nu_R \end{array}}$ if $\boxed{\begin{array}{l} \lambda_e \to V_R\, \lambda_e V_L^\dagger \\ \lambda_\nu \to O_\nu\, \lambda_\nu V_L^\dagger \end{array}}$

- Independent spurions in L_L space: $\lambda_e^\dagger \lambda_e$, $\lambda_\nu^\dagger \lambda_\nu$ [$g_\nu^\dagger g_\nu = (\lambda_\nu^\dagger \lambda_\nu)^2$]